PB86-231222

Status Report on Acid Precipitation and Its Biological Consequences as of April 1981

North Carolina State Univ. at Raleigh

Prepared for

Corvallis Environmental Research Lab., OR

1982

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. R
EPA/600/D-86/164		PB86-231222

4. TITLE AND SUBTITLE	5. REPORT DATE
A Status Report on Acid Precipitation and Its Biological Consequences as of April 1981	1982
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Ellis B. Cowling	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
School of Forest Resources North Carolina State University Raleigh, N.C. 27650	11. CONTRACT/GRANT NO. CR806912
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED Symposium Paper
Environmental Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Corvallis, OR 97333	14. SPONSORING AGENCY CODE 600/02

15. SUPPLEMENTARY NOTES 1982. In pp.3-20. Acid Precipitation: Effects on Ecological Systems, Frank M. d'Itri,ed. Ann Arbor Science Publishers, Ann Arbor, MI. Project Officer: Raymond W. Wilhour, FTS 420-4634

16. ABSTRACT

During the past several years, the phenomenon of acid precipitation and its biological consequences have become a subject of intense public interest. Numberous discussions and debates have been published in the press, in legislative and administrative hearings, and in the board rooms of industry. These discussions often have been based on incomplete awareness of the many atmospheric and biological processes involved.

The purpose of this chapter is to provide a brief, up-to-date, carefully documented, and rigorously peer-reviewed summary of the present status of knowledge about this important environmental issue.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to Public	Unclassified	20
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

EPA/600/D-86/164

CHAPTER 1

A STATUS REPORT ON ACID PRECIPITATION AND ITS BIOLOGICAL CONSEQUENCES AS OF APRIL 1981

Ellis B. Cowling
School of Forest Resources
North Carolina State University
Raleigh, North Carolina 27650

INTRODUCTION

During the past several years, the phenomenon of acid precipitation and its biological consequences have become a subject of intense public interest. Numerous discussions and debates have been published in the press, in legislative and administrative hearings, and in the board rooms of industry. These discussions often have been based on incomplete awareness of the many atmospheric and biological processes involved.

The purpose of this chapter is to provide a brief, up-to-date, carefully documented, and rigorously peer-reviewed summary of the present status of knowledge about this important environmental issue. The summary statements listed below were developed in consultation with many scientists engaged in research on acid precipitation in Europe, Canada, and the United States. In most cases, these summary statements are a synthesis of observations and inferences derived from many independent investigations published prior to April 1981. It is beyond the scope and purpose of this summary to provide rigorous and complete documentation for every point; thus, only a few key investigations are cited for each statement. Complete documentation can be obtained by consulting the original literature, access to which is provided by the following reviews and documents: Abrahamsen, 1980; Almer et al., 1974; Altshuller and McBean, 1979, 1980; Ambio, 1976; Bolin et al., 1972; Braekke, 1976; Cowling, 1980, 1981; Dochinger and Seliga, 1976; Drablós and Tollan, 1980; Galloway et al., 1978; Gorham, 1976; Hendrey, 1978; Howells, 1979; Husar et al., 1978; Hutchinson and Havas, 1980; Likens, 1976; Likens et al., 1979; Malmer, 1973; NAS, 1975; Odén, 1968, 1976; Overrein et al., 1980; and Reuss, 1975.

IN: Acid Precipitation: Effects on Ecological Systems, F. M. d'Itri, ed. Chap. 1, pp 3-20. Ann Arbor Science Publishers, Ann Arbor, MI, 1982

ATMOSPHERIC CHEMISTRY, TRANSPORT, AND DEPOSITION

1. Acid precipitation (rain, snow, hail, dew, fog, frost) is occurring in large regions of the eastern United States and Canada, Europe, and Japan. It has also been reported in certain urban and rural areas in the western United States and Canada and may occur in other regions of the world (Odén, 1968; McColl and Bush, 1978; Likens et al., 1979; Lewis and Grant, 1980).

2. This widespread occurrence of acid precipitation and dry deposition results in large part from man-made emissions of oxides of sulfur and nitrogen. These substances are transformed in the atmosphere to sulfuric and nitric acids, transported over great distances, and deposited on vegetation, soils, surface water, and materials (Smith, 1872, Bolin et al., 1972; Likens, 1976).

3. Acid precipitation is only one special feature of the general phenomenon of atmospheric deposition, which includes three major mechanisms by which substances are transferred from the atmosphere into ecosystems:

   (a) absorption and adsorption of gases,
   (b) impaction and gravitational settling of fine aerosols and coarse particles, and
   (c) precipitation, which includes both dissolved substances and particles that are removed from the atmosphere in rain, snow, hail, dew, fog, and frost.

   Processes a and b are components of dry deposition (Junge and Werby, 1958; Galloway and Cowling, 1978).

4. The acidity (or alkalinity) of precipitation is measured in terms of pH units--the negative logarithm of the concentration of hydrogen ions. Carbon dioxide combines with water in the air to form a dilute solution of carbonic acid at about pH 5.6. For this reason, acid precipitation is arbitrarily defined as precipitation with a pH value below 5.6. Because pH is a logarithmic scale, each unit change in pH represents a ten-fold change in acidity (Odén, 1968; Likens, 1976).

5. Evidence for the occurrence of long-term changes in the acidity of precipitation in North America includes the following:

   (a) changes in average annual pH value of precipitation in the years between 1955-56 and 1975-76,

(b) changes in the alkalinity of surface waters; an especially valuable data set of this sort is available for the Hinckley Reservoir near Utica, New York, between 1924 and 1980,

(c) changes in the amounts and patterns of fuel use in the United States and Canada since the industrial revolution began about 1850; at present, about 95 percent of sulfur emissions in eastern North America are from man-made sources, and

(d) changes in the sulfate and lead content of Greenland ice also since about 1850 (Beamish and Harvey, 1972; Cogbill and Likens, 1974; Cragin et al., 1975; Cronan and Schofield, 1979; Galloway and Whelpdale, 1979).

6. The ratio of sulfate to nitrate ions in precipitation varies from time to time and from place to place. In much of eastern North America the average equivalent ratio of sulfate to nitrate varies from about 3.3:1 in summer to about 0.7:1 in winter. The average annual ratio of sulfuric to nitric acids is currently about 2:1; but nitric acid is becoming progressively more important relative to sulfuric acid (Likens, 1976; Likens et al., 1979; Galloway and Likens, in press).

7. Tall stacks at power plants and smelters decrease nearby ground-level concentrations of SO_2 and NO_x, but simultaneously increase the geographical area of acid deposition. Removal of alkaline particulate matter from stack emissions also increases the acidic character of atmospheric pollutants and, therefore, the acidity of atmospheric deposition (NAS, 1975; Braekke, 1976).

8. Analyses of air-mass movements and chemical transformations in the atmosphere indicate that acid precipitation in one state or region results in part from emissions into the atmosphere in other states or regions, often many hundreds of kilometers from the original source of the emissions (Odén, 1968; OECD, 1977; Galloway and Whelpdale, 1979; Altshuller and McBean, 1979, 1980; Husar and Patterson, 1980; Lyons, 1980).

9. Contemporary precipitation in industrial regions of the world is acidified mainly by man-made emissions of gases and particulate matter. Major anthropogenic sources include combustion of fossil fuels (especially coal and oil), certain industrial processes (especially smelting of ores), exhausts from internal combustion engines, and nitrogen fertilization of agricultural and forest land (Bolin et al., 1972; Kovda, 1975; Likens, 1976).

10. Changes in the acidity of precipitation are reflections of changes in the balance between the major cations and anions in precipitation. Thus, to understand the acidity of precipitation, it is essential to measure all the major anions and cations in precipitation especially hydrogen, sulfate, nitrate, and ammonium ions, but also potassium, sodium, calcium, magnesium, chloride, bicarbonate, sulfite, and phosphate ions (Likens, 1976) .

11. All of the major anions and cations transferred into ecosystems when it is raining or snowing (wet deposition) also are contained in the gases and particulate matter that are transferred from the atmosphere into ecosystems when it is not raining or snowing (dry deposition). Thus, in a chemical mass balance sense, it is both impossible and unrealistic to distinguish the biological effects of "acid precipitation" (wet deposition) from the biological effects of dry deposition (Tamm, 1958; Kovda, 1975; Odén, 1976).

12. Some substances (such as ammonium sulfate) which themselves are not acidic can cause the acidification of soils when they are taken up by plants or modified by soil microorganisms. Thus, the concept of "acidifying precipitation" must be added to the concept of "acid precipitation" (Odén, 1976).

13. The potentially injurious substances in dry and wet deposition include not only acidic substances but also certain toxic gases and organic substances (notably pesticides) as well as various other inorganic substances or heavy metals such as manganese, zinc, copper, iron, molybdenum, boron, chlorine, fluorine, bromine, aluminum, lead, iodine, nickel, cadmium, vanadium, mercury, and arsenic.

GENERAL EFFECTS ON ECOSYSTEMS

1. The elements listed above (item 13) are essential micronutrients needed by plants in small amounts. At higher concentrations, however, each of these same elements (and all the others) can be toxic to plants and animals. Furthermore, the acidity of precipitation can affect the solubility, mobility, and toxicity of certain of these elements. These substances can affect the following:

   (a) the foliage and roots of plants,

(b) animals or microorganisms that may ingest or decompose these plants,
(c) animals (including man) that may drink water containing these elements, and
(d) animals (especially fish and other aquatic organisms) that live in chemical equilibrium with waters containing these substances (Ambio, 1976; Odén, 1976).

2. Significant quantities of plant nutrients, including nitrogen and sulfur, are being added to soil in dry deposition and in precipitation. These atmospheric inputs of beneficial nutrient elements are especially important in forests and rangelands where nutrients from other sources are scarce and where fertilization by man is not a normal management procedure (Hooke, 1687; Tamm, 1958; Wittwer and Bukovac, 1969; Cowling, 1980).

3. Short-term fertilization effects due to atmospheric deposition of ammonia and nitrate tend to offset long-term nutrient leaching and other detrimental effects of acid precipitation on forest ecosystems. Negative effects of atmospheric deposition on forest growth are most likely when nutrient deficiencies or imbalances are increased by acid deposition (Abrahamsen, 1980).

4. The net effect of atmospheric deposition can be beneficial or injurious to plants and animals depending on the chemical composition of the deposition (wet and dry), the duration and intensity of deposition episodes, the species and genetic characteristics of the organisms on which the substances are deposited, and the physiological condition, structure, and stage of maturity of the organisms (Grahn et al., 1976; Abrahamsen, 1980; Cowling, 1980; Lee et al., 1980).

5. Damage or injury to aquatic or terrestrial organisms is most likely when a particularly sensitive life form or life stage developing in poorly buffered waters or soils coincides with major episodic inputs of acid precipitation or other injurious substances (Borgstrøm and Hendrey, 1976; Leivestad et al., 1976; Likens et al., 1979; Hall et al., 1980).

6. Regions of greatest sensitivity to acid precipitation usually are recently glaciated, with large areas of exposed granitic (crystalline) and other non-calcareous bedrock and thin soils that are low in buffering and cation exchange capacity (Reuss, 1975; McFee, 1978; Abrahamsen, 1980).

7. Terrestrial and aquatic ecosystems are so intimately linked that it is both impossible and unrealistic to consider the effects of acid precipitation in aquatic ecosystems without considering its effects on terrestrial vegetation, soils, and the geology of the drainage basin (Braekke, 1976; Odén, 1976).

EFFECTS ON AQUATIC ECOSYSTEMS

1. Acids and other soluble substances contained in polluted snow are released as contaminated meltwater during warm periods in winter or in early spring. The resulting release of pollutants can cause major and rapid changes in the acidity and other chemical properties of stream and lake waters. Fish kills are a dramatic consequence of such episodic inputs into aquatic ecosystems (Odén and Ahl, 1970; Leivestad et al., 1976).

2. Acid precipitation titrates the acidity/alkalinity of lake and stream waters from conditions that are favorable for fish and other aquatic organisms to conditions that inhibit reproduction and/or recruitment of populations of fish and fish-food organisms (Hendrey and Wright, 1975; Henriksen, 1979; Leivestad et al., 1976; Henriksen, 1980).

3. In oligotrophic lakes and streams between pH 6.0 and pH 5.0, reproduction of certain species of aquatic organisms is inhibited; below pH 5.0, populations of many freshwater fish will become extinct (Beamish and Harvey, 1972; Dickson et al., 1973; Leivestad et al., 1976; Schofield, 1976).

4. Interference with normal reproductive processes in fish populations is induced not only by acidity itself but also by increased concentrations of certain cations, notably aluminum, in acidified lake and stream waters. Aluminum compounds vary greatly in toxicity to fish and other aquatic life. In general, ionic forms of aluminum are more toxic than aluminum complexed with organic matter (Hultberg and Grahn,1976; Cronan and Schofield, 1979; Driscoll, 1980).

5. Reproduction of frogs and salamanders also is inhibited by atmospheric acidification of surface waters (Pough, 1976; Hagström, 1977).

6. As of 1980, hundreds of lakes in the Adirondack region of New York State, and many hundreds of lakes in various parts

of southern Ontario and Quebec were showing acid stress in the form of diminished populations or extinction of fish populations. Lakes and streams in other regions of the United States and Canada also are vulnerable to stress by acid precipitation. These regions include northern Minnesota, Wisconsin, and Michigan; parts of southern Appalachia and Florida, and large parts of Washington, Oregon, California, and Idaho, and parts of the Canadian Maritime Provinces (Beamish and Harvey, 1972; Schofield, 1976; Galloway and Cowling, 1978; Altshuller and McBean, 1979; Hendrey et al., 1980).

EFFECTS ON AGRICULTURAL CROPS AND FORESTS

1. In certain industrial regions of the world, substantial damage to forests and agricultural crops is caused by the dry deposition of toxic gases. Sulfur dioxide, ozone, oxides of nitrogen, fluoride, and hydrogen chloride cause serious economic damage to crops and forests that must be considered together with the possible effects of acid deposition. Recent experiments have shown that a combination of acid precipitation and ozone caused greater reduction in yield of soybeans than ozone alone (Heck and Brandt, 1977; Shriner et al., 1980; J. Trioiano, personal communication).

2. Direct and indirect damage to crops and forests have been reported in laboratory, greenhouse, and field experiments in which synthetic rain equivalent (in chemical composition and rate of deposition) to natural rains has been applied. These biological effects include the following:

   (a) Induction of necrotic lesions and other morphological changes in foliage (Shriner, 1978; Evans and Curry, 1979).
   (b) Loss of nutrients due to leaching from foliar organs (Wood and Bormann, 1974).
   (c) Predisposition of plants to infection by bacterial and fungal pathogens (Shriner, 1978).
   (d) Accelerated erosion of waxes on leaf surfaces (Shriner, 1976).
   (e) Inhibition of nodulation of legumes leading to decreased nitrogen fixation by symbiotic bacteria (Shriner and Johnston, 1980).
   (f) Reduced rates of decomposition of leaf litter leading to decreased mineralization of organically-bound nutrients (Abrahamsen, 1980).

(g) Inhibited formation of terminal buds and increased mortality of pine seedlings (Matziris and Nakos, 1977).
(h) Both decreased and increased yield of certain agricultural crops (Evans and Lewin, 1980; Evans et al., 1980; Lee et al., 1980).
(i) Interference with normal reproductive processes (Evans and Conway, 1980).

3. Various specific biological effects of simulated acid rain have been demonstrated in controlled field and laboratory experiments (see item 2 above), but reliable evidence of economic damage to agricultural crops, forest, and other vegetation, and to biological processes in soil by naturally occurring precipitation has been reported only rarely (Jonsson and Sundburg, 1972; Galloway et al., 1978; Cowling, 1980; Ulrich and Khanna, 1980; Tomlinson, 1981).

4. Recent experiments in Germany have demonstrated a significant correlation between amount of soluble aluminum in forest soils, death of feeder roots in spruce, fir, and beech forests, and widespread decline in the growth of these forests. Acid precipitation and dry deposition of acid-yielding substances have been postulated as probable causes of these coincident effects (Ulrich et al., 1980; Schuck et al., 1979; Tomlinson, 1981).

5. Mushrooms, mosses, lichens, and other lesser vegetation in forests accumulate heavy metals from the atmosphere, especially lead and cadmium. Wildlife feeding on these plants themselves accumulate the metals, sometimes making both the plants and the wildlife hazardous for human consumption (Munshower, 1972; Huckabee and Blaylock, 1974; Tyler, 1980).

EFFECTS ON SOILS

1. The consequences of acid inputs to soils vary greatly, depending upon the rates and recent history of atmospheric acid inputs, the character of the vegetation, natural rates of acid formation in the soil, and the physical-chemical properties of the soil (Wiklander, 1973; McFee, 1978).

2. Soil acidification increases leaching of exchangeable plant nutrients such as calcium, magnesium, potassium, iron, and manganese, and increases the rate of weathering of most minerals (Overrein, 1972; Reuss, 1975; Odén, 1976).

3. Acidification decreases the rate of many soil microbial processes such as nitrogen fixation and breakdown of organic matter. Various processes important in nutrient cycling, and critical in most ecosystems, are known to be inhibited by lowering soil pH. Included are the following: nitrogen fixation by Rhizobium bacteria on leguminous plants, by actinomycetes on some non-leguminous plants, and by certain blue-green algae and bacteria; mineralization of nitrogen from forest litter; nitrification of ammonium compounds; and overall decay rates of forest floor materials (Reuss, 1975; Braekke, 1976; Francis et al., 1980; Shriner and Johnston, 1980).

4. Atmospheric deposition of heavy metals also inhibits certain microbial processes in forest litter, especially decomposition of organic matter (Braekke, 1976; Tyler, 1976).

5. Acidification of soils reduces the availability of phosphorus to plants and increases the solubility of other elements, some of which may be toxic to plants. Aluminum is the most abundant toxic element in most forest and agricultural soils. Increasing soil acidity leads to greatly increased solubility and toxicity of aluminum to many crop and forest plants (Odén, 1976; Tomlinson, 1981).

6. Soils differ by orders of magnitude in their susceptibility to acidification. Calcareous soils are unlikely to be damaged by acid inputs, but may be affected by metal deposition. Soils with low cation exchange capacity and degree of base saturation are very susceptible to increased acidification (Reuss, 1975; McFee, 1978).

7. Large quantities of hydrogen ions are added to soils as acid precipitation and as a result of cation uptake processes and both soil-amendment and fertilization practices. Acidification by these processes can be controlled by normal management practices in cultivated soils. But large areas of North America and Europe are not cultivated and have soils that are poorly buffered and, therefore, are susceptible to further acidification. Many of these soils occur in forest and wilderness areas (Reuss, 1975; Odén, 1976).

EFFECTS ON WATER QUALITY

1. The chemical composition of lake, stream, and groundwaters is determined in part by the chemical composition of

precipitation and dry deposition. The chemical composition of precipitation is modified by chemical and biological weathering and exchange processes as precipitation: washes over vegetation; percolates through the soil; interacts with the underlying bedrock of the drainage basin in which the precipitation occurs; and runs off over the soil surface (Braekke, 1976; Odén, 1976).

2. Acid precipitation increases the solubility and mobility of many cations in soil. This increases the concentration of toxic metal cations, including aluminum, manganese, and zinc, in the soil solution. It also increases the leaching of nutrient cations, including potassium, calcium, magnesium, etc. These toxic and nutrient ions are transferred from soils into surface and groundwaters (Braekke, 1976; Odén, 1976).

3. Acidification of groundwaters has been found in western Sweden and attributed to long-term changes in the acidity of precipitation. As a result, hundreds of shallow dug wells and deeper drilled wells for home and farm buildings have shown acidities in the range between pH 4.0 and pH 6.0. A strong positive correlation has been found between the acidity of the well water and the content of metal ions, including copper, zinc, lead, manganese, and aluminum. In some cases, accelerated corrosion of copper piping has resulted in the necessity for early repair and/or replacement of copper piping systems (Hultberg and Wenblad, 1980).

LITERATURE CITED

Abrahamsen, G. 1980. Acid Precipitation, Plant Nutrients, and Forest Growth. In: D. Drabløs and A. Tollan, eds., "Ecological Impacts of Acid Precipitation," Proc. Intern. Conf., Sandefjord, Norway. SNSF Project Report, Ås, Norway.

Almer, B., W. Dickson, C. Ekström, E. Hörnström, and U. Miller. 1974. Effects of Acidification on Swedish Lakes. Ambio 3:30-36.

Altshuller, A.P. and G.A. McBean, Co-chairmen. 1979. The LRTAP Problem in North America: A Preliminary Overview Prepared by the United States-Canada Bilateral Research Consultation Group on the Long-Range Transport of Air Pollutants. Atmospheric Environment Service, Downsview, Ontario. Part I (1979), 48 pp.; Part II (1980), 39 pp.

Ambio. 1976. Report of the International Conference on the Effects of Acid Precipitation in Telemark, Norway. Ambio 5:200-252.

Beamish, R.J. and H.H. Harvey. 1972. Acidification of the LaCloche Mountain Lakes, Ontario, and Resulting Fish Mortalities. J. Fish. Res. Bd. of Can. 29:1131-1143.

Bolin, B., L. Granat, L.Ingelstom, M. Johannesson, E. Mattsson, S. Odén, H. Rodhe, and C.O. Tamm. 1972. Sweden's Case Study for the United Nations Conference on the Human Environment: Air Pollution Across National Boundaries. The Impact on the Environment of Sulfur in Air and Precipitation. Norstadt and Sons, Stockholm. 97 pp.

Borgstrom, R. and G.R. Hendrey. 1976. pH Tolerance of the First Level Stages of Lepidurus arcticus (pallas) and Adult Gammarus lacustris G.O. Sars. Internal Report22/76, SNSF Project, Ås, Norway.

Braekke, F.H. (ed.). 1976. Impact of Acid Precipitation on Forest and Freshwater Ecosystems in Norway. Res. Rep. 6/76, SNSF Project, Ås, Norway. 111 pp.

Cogbill, C.V. and G.E. Likens. 1974. Acid Precipitation in the Northeastern United States. Water Resources Res. 10:1133-1137.

Cowling, E.B. 1980. Acid Precipitation and Its Effects on Terrestrial and Aquatic Ecosystems. In: T.J. Kneip and P.J. Lioy, eds., "Aerosols: Anthropogenic and Natural, Sources and Transport." Annals New York Academy of Science 338:540-555.

Cowling, E.B. 1981. An Historical Résumé of Progress in Scientific and Public Understanding of Acid Precipitation and Its Biological Consequences. Research Report, SNSF Project, Ås, Norway.

Cragin, J.H., M. Herron, and C.C. Langway, Jr. 1975. The Chemistry of 700 Years of Precipitation at Dye-3 Greenland. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire. 18 pp.

Cronan, C.S. and C.L. Schofield. 1979. Aluminum Leaching Response to Acid Precipitation: Effects on High-level Watersheds in the Northeast. Science 204:304-305.

Dickson, W., C. Ekström, E. Hörnström, and U. Miller. 1973. Forsurningens inverkan på vastkustsjoar. (The Effects of Acidification of West-Coast Lakes.) Swedish National Environmental Protection Board, Stockholm, Publ. No. 7. 97 pp.

Dochinger, L.S. and T.A. Seliga. 1976. Proceedings First International Symposium on Acid Precipitation and the Forest Ecosystem. USDA Forest Serivce, Gen. Tech. Rept. NE-23, Northeast, For. Exp. Sta., Upper Darby, Pennsylvania. 1079 pp.

Drabløs, D. and A. Tollan (eds.). 1980. Ecological Impact of Acid Precipitation. Proc. Intern. Conf., Sandefjord, Norway. SNSF Project, Ås, Norway. 383 pp.

Driscoll, C.T. 1980. Aqueous Speciation of Aluminum in the Adirondack Region of New York State, USA. In: D. Drabløs and A. Tollan, eds., "Ecological Impact of Acid Precipitation," pp. 214-215. Proc. Intern. Conf., Sandefjord, Norway. SNSF Project, Ås, Norway.

Evans, L.S. and C.A. Conway. 1980. Effects of Acidic Solutions on Sexual Reproduction of Pteridium aquilinum. Amer. J. Bot. 67:866-875.

Evans, L.S., C.A. Conway, and K.F. Lewin. 1980. Yield Responses of Field-Grown Soybeans Exposed to Simulated Acid Rain. In: D. Drabløs and A. Tollan, eds., "Ecological Impact of Acid Precipitation," pp. 162-163. Proc. Intern. Conf., Sandefjord, Norway. SNSF Project, Ås, Norway.

Evans, L.S. and T.M. Curry. 1979. Differential Responses of Plant Foliage to Simulated Acid Rain. Amer. J. Bot. 66:953-962.

Evans, L.S. and K.F. Lewin. 1980. Growth, Development, and Yield Responses of Pinto Beans and Soybeans to Hydrogen Ion Concentrations of Simulated Acidic Rain. Environ. and Exp. Bot. 21:103-113.

Francis, A.J., D. Olson, and R. Bernatsky. 1980. Effects of Acidity on Microbial Processes in a Forest Soil. In: D. Drabløs and A. Tollan, eds., "Ecological Impacts of Acid Precipitation," pp. 166-167. Proc. Intern. Conf., Sandefjord, Norway. SNSF Research Report, Ås, Norway.

Galloway, J.N. and E.B. Cowling. 1978. The Effects of Precipitation on Aquatic and Terrestrial Ecosystems: A Proposed Precipitation Chemistry Network. J. Air Pollut. Cont. Assoc. 28:228-235.

Galloway, J.N., E.B. Cowling, E. Gorham, and W.W. McFee. 1978. A National Program for Assessing the Problem of Atmospheric Deposition (Acid Rain). Nat. Atm. Dep. Prog., Nat. Res. Ecol. Lab., Fort Collins, Colorado. 97 pp.

Galloway, J.N., S.F. Eisenreich, and B.C. Scott (eds.). 1980. Toxic Substances in Atmospheric Deposition: A Review and Assessment. NADP Special Report. Nat. Atm. Dept. Prog., Nat. Res. Ecol. Lab., Fort Collins, Colorado. 217 pp.

Galloway, J.N. and G.E. Likens. 1980. Acid Precipitation: The Importance of Nitric Acid. Atmos. Environ. (in press).

Galloway, J.N. and D.M. Whelpdale. 1979. An Atmospheric Sulfur Budget for Eastern North America. Atmos. Environ. 14:409-417.

Gorham, E. 1961. Factors Influencing Supply of Major Ions to Inland Waters, With Special Reference to the Atmosphere. Geol. Soc. Amer. Bull. 72:795-840.

Gorham, E. 1976. Acid Precpitation and Its Influence Upon Aquatic Ecosystems - An Overview. Water Air Soil Pollut. 6:457-481.

Gorham, E. and A.G. Gordon. 1960. The Influence of Smelter Fumes Upon the Chemical Composition of Lake Waters Near Sudbury, Ontario, and Upon the Surrounding Vegetation. Can. J. Bot. 38:477-487.

Grahn, O., H. Hultberg, and L. Landner. 1974. Oligotrophication — A Self-Accelerating Process in Lakes Subjected to Excessive Supply of Acid Substances. Ambio 3:93-94.

Hagström, T. 1977. Grodornas forsvinnande i en försurad sjö. (Disappearance of Frogs in an Acidified Lake.) Sveriges Natur 11:367-369.

Hall, R.J., G.E. Likens, S.B. Fiance, and G.R. Hendrey. 1980. Experimental Acidification of a Stream in the Hubbard Brook Experimental Forest, New Hampshire. Ecology 61:976-989.

Heck, W.W. and C.S. Brandt. 1977. Effects on Vegetation: Native, Crops, Forests. In: A.C. Stern, ed., "Air Pollution," Vol. II, pp. 157-229. Academic Press, New York.

Hendrey, G.R. 1978. Limnological Aspects of Acid Precipitation. Proceedings International Workshop, Sagamore Lake, New York. Brookhaven National Laboratory, Upton, New York. 66 pp.

Hendrey, G.R., J.N. Galloway, S.A. Norton, C.L. Schofield, D.A. Burns, and P.W. Schaffer. 1980. Sensitivity of the Eastern United States to Acid Precipitation Impacts on Surface Waters. In: D. Drablós and A. Tollan, eds., "Ecological Impact of Acid Precipitation," pp. 216-217. Proc. Intern. Conf., Sandefjord, Norway. SNSF Project Report, Ås, Norway.

Hendrey, G.R. and R.F. Wright. 1975. Acid Precipitation in Norway: Effects on Aquatic Fauna. J. Great Lakes Res. 2 (Suppl. 1):192-207.

Henriksen, A. 1980. Acidification of Freshwaters - A Large Scale Titration. In: D. Drablós and A. Tollan, eds., "Ecological Impact of Acid Precipitation," pp. 68-74. Proc. Intern. Conf., Sandefjord, Norway. SNSF Project, Ås, Norway.

Henriksen, A. 1979. A Simple Approach for Identifying and Measuring Acidification of Freshwater. Nature 278:542-545.

Hooke, R. 1687. An Account of Several Curious Observations and Experiments Concerning the Growth of Trees. Phil. Trans. Royal Soc. London 16:207-313.

Howells, G. 1979. Ecological Effects of Acid Precipitation. Proceedings of a Workshop held at Galloway, Scotland, Sept. 1978. Central Electricity Research Laboratories, Leatherhead, Surrey, England.

Huckabee, J.W. and B.G. Blaylock. 1974. Microcosm Studies on the Transfer of Hg, Cd, and Se From Terrestrial to Aquatic Ecosystems. In: D.D. Hemphill, ed., "Proceedings Univ. of Missouri 8th Annual Conference on Trace Substances in Environmental Health," Columbia, Missouri.

Hultberg, H. and O. Grahn. 1976. Proceedings of the First Specialty Symposium on Atmospheric Contributions to the Chemistry of Lake Waters. J. Great Lakes Res. 2 (Suppl. 1), 208 pp.

Hultberg, H. and A. Wenblad. 1980. Acid Ground Water in Southwestern Sweden. In: D. Drablós and A. Tollan, eds., "Ecological Impact of Acid Precipitation," pp. 220-221. Proc. Intern. Conf., Sandefjord, Norway. SNSF Project, Ås, Norway.

Husar, R.B., J.P. Lodge, Jr., and D.J. Moore (eds.). 1978. Sulfur in the Atmosphere. Atmos. Environ. 12:1-3 (special issue). 796 pp.

Husar, R.B. and D.E. Patterson. 1980. Regional Scale Air Pollution: Sources and Effects. In: T.J. Kneip and P.J. Lioy, eds., "Aerosols: Anthropogenic and Natural, Sources and Transport," pp. 399-417. Annals New York Academy of Sciences 338.

Hutchinson, T.C. and L.M. Whitby. 1974. Heavy Metal Pollution in the Sudbury Mining and Smelting Region of Canada. 1. Soil and Vegetation Contamination by Nickel, Copper, and Other Metals. Environ. Conserv 1(2):123.

Hutchinson, T.C. and M. Havas (eds.). 1980. Effects of Acid Precipitation on Terrestrial Ecosystems. Plenum Press, New York. 654 pp.

Jonsson, B. and R. Sundberg. 1972. Has the Acidification by Atmospheric Pollution Caused a Growth Reduction in Swedish Forests? Research Note No. 20, Department of Forest Yield Research, Royal College of Forestry, Stockholm, Sweden. 48 pp.

Junge, G.E. and R. Werby. 1958. The Concentration of Chloride, Sodium, Potassium, Calcium, and Sulfate in Rain Water Over the United States. J. Meteorol. 15:417-425.

Kovda, V.A. 1975. Biogeochemical Cycles in Nature, Their Disturbance and Study. (In Russian) Kuaka Publishing House, Moscow, USSR.

Lee, J.J., G.E. Neely, and S.C. Perregar.. 1980. Sulfuric Acid Rain Effects on Crop Yield and Foliar Injury. U.S. Environmental Protection Agency, Report No. EPA-600/3-80-016. 21 pp.

Leivestad, H., G. Hendrey, I.P. Muniz, and E. Snekvik. 1976. Effects of Acid Precipitation on Fresh Water Organisms. In: F.H. Braekke, ed., "Impact of Acid Precipitation on Forest and Freshwater Ecosystems in Norway," pp. 86-111. Research Report FR 6-76. SNSF Project, Ås, Norway.

Leivestad, H. and I.P. Muniz. 1976. Fish Kill at Low pH in a Norwegian River. Nature 251:391-392.

Lewis, W.M., Jr. and M.C. Grant. 1980. Acid Precipitation in the Western U.S. Science 207:176-177.

Likens, G.E. 1976. Acid Precipitation. Chem. Eng. News 54(48):29-44.

Likens, G.E., R.F. Wright, J.N. Galloway, and T.J. Butler. 1979. Acid Rain. Sci. Amer. 241(4):43-51.

Lyons, W.A. 1980. Evidence of Transport of Hazy Air Masses from Satellite Imagery. In: T.J. Kneip and P.J. Lioy, eds., "Aerosols: Anthropogenic and Natural, Sources and Transport." Annals New York Academy of Science 338:418-433.

Malmer, D. 1973. Om effecterna på vatten, mark och vegetation av ökad svaveltillförsel från atmosfären. (On the Effects of Water, Soil, and Vegetation from an Increasing Atmospheric Supply of Sulfur.) Statens Natur Vardawerk, Lunds Universitet, Lund, Sweden. 125 pp.

Matziris, D.I. and G. Nakos. 1977. Effects of Simulated "Acid Rain" on Juvenile Characteristics of Aleppo Pine (Pinus halepensis Mill.). Forest Ecol. Mgmt. 1:267-272.

McColl, J.G. and D.S. Bush. 1978. Precipitation and Throughfall Chemistry in the San Francisco Bay Area. J. Environ. Qual. 7:352-357.

McFee, W.W. 1978. Effects of Acid Precipitation and Atmospheric Deposition on Soils. In: J.N. Galloway, E.B. Cowling, E. Gorham, and W.W. McFee, eds., "A National Program for Assessing the Problem of Atmospheric Deposition (Acid Rain)," pp. 64-73. Nat. Atm. Dep. Prog., National Research Ecol. Lab., Fort Collins, Colorado.

Munshower, F.F. 1972. Cadmium Compartmentation and Cycling in Grassland Ecosystems in the Deer Lodge Valley. Ph.D. Thesis, Univ. Montana, Bozeman, Montana.

National Academy of Sciences. 1975. Atmospheric Chemistry: Problems and Scope. Com. Atm. Sci., Nat. Res. Council, Washington, D.C. 130 pp.

Odén, S. 1968. The Acidification of Air and Precipitation and Its Consequences in the Natural Environment. Ecology Committee Bulletin No. 1, Swedish National Science Research Council, Stockholm. Translation Consultants, Ltd., Arlington, Virginia. 117 pp.

Odén, S. 1976. The Acidity Problem - An Outline of Concepts. Water Air Soil Pollut 6:137-166.

Odén, S. and T. Ahl. 1970. Forsurningen av skandenaviska vatten. (The Acidification of Scandinavian Lakes and Rivers.) Ymer, Arsbok:103-122.

Organization for Economic Cooperation and Development. 1977. The OECD Program on Long Range Transport of Air Pollutants. OECD, Paris, France.

Overrein, L.N. 1972. Sulphur Pollution Patterns Observed; Leaching of Calcium in Forest Soil Determined. Ambio 1:145-147.

Overrein, L.N., H.M. Seip, and A. Tollan. 1980. Acid Precipitation - Effects on Forests and Fish. Final report of the SNSF Project 1972-1980, Research Report FR-19. SNSF Project, Ås, Norway. 175 pp.

Pough, F.H. 1976. Acid Precipitation and Embryonic Mortality of Spotted Salamanders, Ambystoma maculatum. Science 192:68-70.

Reuss, J.O. 1975. Chemical/Biological Relationships Relevant to Ecological Effects of Acid Rainfall. EPA Report 600/3-75-032. Environmental Protection Agency, Washington, D.C.

Schofield, C.L. 1976. Effects of Acid Precpitation on Fish. Ambio 5:228-230.

Schuck, H.J., U. Blumel, I. Geier, and O. Schutt. 1979. Schadbild und atiologie des tannesterbens. Eur. J. For. Path. 10:125-135.

Shriner, D.S. 1976. Effects of Simulated Rain Acidified with Sulfur Acid on Host-Parasite Interactions. In: L.S. Dochinger and T.A. Seliga, eds., "Proc. Int. Symp. on Acid Precipitation and the Forest Ecosystem," pp.919-925. USDA For. Serv. Gen. Tech. Rep. NE-23, Upper Darby, Pennsylvania.

Shriner, D.S. 1978. Effects of Simulated Acidic Rain on Host-Parasite Interactions in Plant Disease. Phytopathology 68:213-218.

Shriner, D.S. and J.W. Johnston. 1980. The Effect of Simulated Acidified Rain on Nodulation of Leguminous Plants by Rhizobium spp. Environ. and Exp. Bot. 21:199-209.

Shriner, D.S., C.R. Richmond, and S.E. Lindberg (eds.). 1980. Atmospheric Sulfur Deposition: Environmental Impact and Health Effects. Ann Arbor Science Pub., Ann Arbor, Michigan. 568 pp.

Smith, R.A. 1872. Air and Rain: The Beginning of a Chemical Climatology. Longmans, Green, London. 600 pp.

Tamm, C.O. 1958. The Atmosphere. Handbuch fur Pflanzen-physiologie 6:233-242.

Tomlinson, G.H. 1981. Acid Rain and the Forest - The Effect of Aluminum and the German Experience. DOMTAR Research Center, Sennerville, Quebec, Canada. 22 pp.

Tyler, G. 1972. Heavy Metals Pollute Nature, May Reduce Productivity. Ambio 1:52-59.

Tyler, G. 1976. Heavy Metal Pollution, Phosphatase Activity, and Mineralization of Organic Phosphorus in Forest Soils. Soil Biol. Biochem. 8:327-332.

Tyler, G. 1980. Metals in Sporophores of Basidiomycetes. Trans. Brit. Myc. Soc. 24:41-49.

Ulrich, B., R. Mayer, and P.K. Khana. 1980. Chemical Changes Due to Acid Precipitation in a Loess Derived Soil in Central Europe. Soil Sci. 130:193-199.

Wiklander, L. 1973. The Acidification of Soil by Acid Precipitation. Gundforbattring 26(4):155-164.

Wittwer, S.H. and M.J. Bukovac. 1969. The Uptake of Nutrients Through Leaf Surfaces. In: K. Scharrer and H. Linser, eds., "Handbuch der Pflanzenernahrung und Dungung," pp. 235-261. Springer-Verlag, New York.

Wood, T. and F.H. Bormann. 1974. The Effects of an Artificial Acid Mist Upon the Growth of Betula alleghanien-sis Britt. Environ. Pollut. 7:259-268.